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In recent years, scientists from such diverse fields as geophysics, seafloor engineering, sedimentology, soil mechanics, and underwater acoustics have devoted considerable attention to the measurement of sediment shear wave velocity and/or sediment dynamic modulus. These fundamental sediment properties are important to predicting the stability of sediment slopes, the consolidation behavior of sediments, the strength of marine foundations, and the conversion of water-borne energy to sediment shear wave energy at the seabottom, to give just a few examples.

Sediment shear wave velocity has been measured in situ using probes deployed by scuba divers, submersibles (Hamilton et al., 1970), and remotely from surface ships (Bennell et al., 1982). Shear wave velocity has also been measured in between boreholes using explosive and various vibratory techniques (Warrick, 1974). Scholte waves and statistic Love waves have been used to estimate shear wave velocities in surficial sediments by numerous investigators (Rauch, 1986; Akal et al., 1986; Snoek, 1990).

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CHAPTER 44

Sediment Shear Waves: A Comparison of *In Situ* and Laboratory Measurements

Michael D. Richardson, Enrico Muzi, Luigi Troiano, and Bruno Miaschi

Introduction

In recent years, scientists from such diverse fields as geophysics, seafloor engineering, sedimentology, soil mechanics, and underwater acoustics have devoted considerable attention to the measurement of sediment shear wave velocity and/or sediment dynamic modulus. These fundamental sediment properties are important to predicting the stability of sediment slopes, the consolidation behavior of sediments, the strength of marine foundations, and the conversion of water-borne energy to sediment shear wave energy at the seabottom, to give just a few examples.

Sediment shear wave velocity has been measured *in situ* using probes deployed by scuba divers, submersibles (Hamilton et al., 1970), and remotely from surface ships (Bennell et al., 1982). Shear wave velocity has also been measured in and between boreholes using explosive and various vibratory techniques (Warrick, 1974). Scholte waves and Love waves have been used to estimate shear wave velocities in surficial sediments by numerous investigators (Rauch, 1986; Akal et al., 1986; Snoek, 1990).

Hamilton (1976, 1980, 1987), in recent reviews of *in situ* measurements of shear wave velocity, found that the relatively few good measurements had such a wide range of values as to make the prediction of shear wave velocity in surficial sediments difficult and tenuous. Hamilton reported typical velocities of 50–150 m/sec in the upper meter of clays increasing to 100–200 m/sec at 10 m depth. Sands had similar values for the upper meter of the sediment increasing to 200–300 m/sec at 10 m.

Numerous attempts have been made to measure shear wave velocity of natural and artificial sediments in the laboratory. Many of these measurements have been based on the ceramic bender transducer technology pioneered by Shirley (1978). Shear wave velocities have been measured on freshly cut cores (Richardson, 1983; Richardson et al., 1987; Schultheiss, 1985; Lavoie 1988). Shear wave velocities have also been measured on artificial sediments at atmospheric pressure (Horn, 1980; Brunson and Johnson, 1980) and under confining pressures meant to represent consolidation under several meters of sediment (Schultheiss, 1981). Lovell and Ogden (1984) measured shear wave velocity gradients on both surficial and naturally consolidated sediments under confining pressures representing 0–400 m overburden pressure. Laboratory measurements of shear wave velocity have also been made using the resonant column test (see Hardin and Richart, 1963 for a review of these techniques). Shear wave velocities as low as 2 m/sec have been reported for artificial sediments created from settled kaolinite (Shirley and Hampton, 1978) and typical velocities of 20 m/sec (silts and clays) and 50 m/sec (sands) have been reported for surficial sediments collected with cores (Richardson et al., 1987).

Seismic refraction techniques (Danbom and Domenico, 1987) have also been used to determine shear wave velocities in marine sediments, but these techniques integrate shear wave velocities over profiles kilometers long and hundreds of meters thick. More short-range seismic experiments, such as those reported by Stoll et al. (1988), are required to determine sediment geoacoustic properties in the upper few meters of sediments. Recent advances in deep-towed seismic sources and receivers will also increase the vertical resolution of these techniques (Fagot, 1986).

Shear wave velocity can be estimated using the empirical relationships of Hamilton (1971, 1976, 1987) and Bryan and Stoll (1988) or calculated from physical models such as the Biot–Stoll Model (Ogushwitz, 1985; Biot, 1962; Stoll, 1980). Both models (given appropriate depth dependent input parameters), as well as empirical relationships, can be used to estimate shear wave velocity with depth in the sediment. The relatively few shear wave measurements, differences in measurement techniques, and a controversy about the actual physical mechanisms that

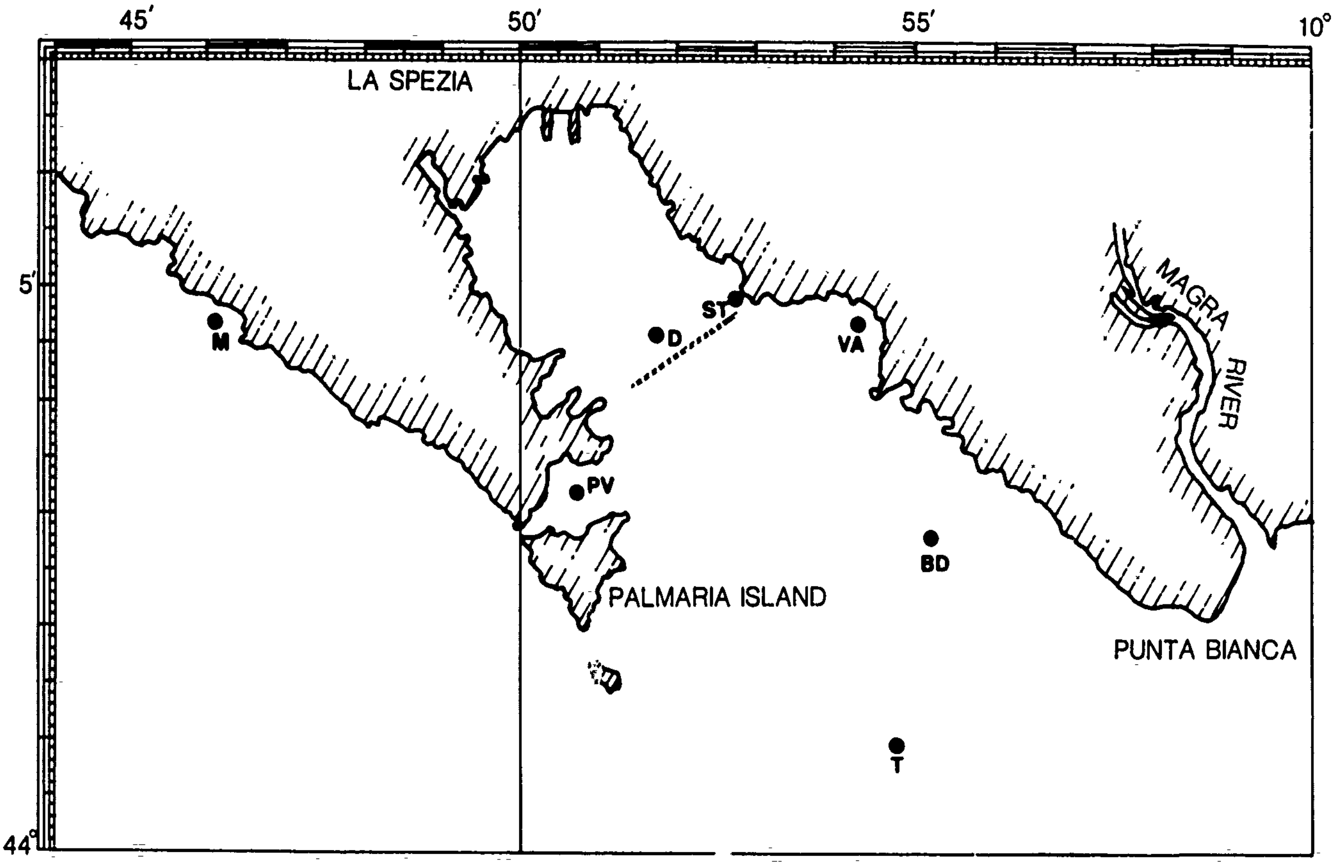

Figure 44.1. Location of sampling sites: Diga (D), Venere Azzura (VA), Santa Teresa (ST), Portovenere (PV), Turf (T), Boa Dragaggio (BD), and Monasteroli (M). Viareggio site (43° 48.62'N, 10° 07.16'E) was 33 km southeast of Palmaria Island.

control this type of low strain acoustic propagation have led to a rather confused picture as to the actual velocities of shear waves in surficial marine sediments.

It is the purpose of this chapter to compare values of shear wave velocity obtained both *in situ* and in the laboratory using similar measurement techniques. The existence of an empirical relationship between *it situ* and laboratory shear wave velocity is explored. Empirical relationships between *in situ* shear wave velocity and easily measured sediment physical properties are examined. Hamilton (1987) laments the lack of *in situ* measurements in modern marine sediments. The data we present and measurement techniques we develop will help fill this void and lead to an improved fundamental understanding of the propagation of acoustic waves through marine sediments.

Materials and Methods

General

Eight sites were chosen to represent a wide selection of sediment types within diving depths (Fig. 44.1). Several of the sites have been the locations for saclantcen acoustic and geoacoustic experiments conducted over the last 6 years (Rauch, 1980, 1986; Akal et al., 1984, 1986; Richardson, 1986; Schmalfeldt, 1986; Snoek et al., 1986; Snoek and Rauch, 1987; Snoek, in press).

Sediments were collected using a 12.0-cm-inside diameter PVC hand-operated corer. At least three cores were collected at each site. Nearbottom temperature and salinity were measured by scuba divers using hand-held probes. *In situ* shear wave velocity measurements were made with the probes described in the next section. At least three deployments were made at each station. Sediment cores were carefully transported to the laboratory and kept under refrigeration at 4°C until laboratory shear wave velocity measurements were made. After the acoustic measurements, sediment samples were collected from each core for mass property determination. All data, reported herein, were measured from sediments at or collected from 30 cm below the sediment-water interface.

A summary of environmental conditions for each station occupancy is given in Table 44.1. During our study measured salinities ranged from 37.5 to 38 ppt and are not reported for each deployment.

Table 43.1. Summary of environmental conditions for the eight sampling sites (some sites sampled more than once).

Site	Depth (m)	Date	Temperature (°C)	Sediment type	Porosity (%)	Density (g m^{-3})
Diga	7	6 October 87	26.0	Silty-clay	69.2	1.54
Diga	6	14 March 88	12.4	Silty-clay	68.9	1.54
Venere Azzura	7	15 March 88	12.5	Sand	47.1	1.88
Santa Teresa	10	17 March 88	12.5	Silty-clay	67.5	1.54
Portovenere	12	18 March 88	12.5	Silty-clay	63.4	1.63
Turf	18	27 April 88	14.5	Silty-sand	50.8	1.83
Diga	7	28 April 88	14.5	Silty-clay	–	–
Boa Dragaggio	14	30 April 88	14.5	Sand/silty-clay	57.9	1.71
Venere Azzura	7	25 July 88	24.1	Sand	43.7	1.91
Monasteroli	16	28 July 88	19.5	Sand	43.7	1.91
Turf	18	28 July 88	18.8	Sand/silty-clay	52.6	1.77
Viareggio	22	29 July 88	19.5	Silty-clay	61.9	1.60

In Situ Measurements

Sediment shear wave velocity was measured using a pulse technique. Transmitters and receivers were identical 1.25 in. (31.75 mm) square × 0.019 in. (0.48 mm) thick bimorph ceramic benders (Fig. 44.2). The ceramics were potted in a stainless-steel ring with silicone rubber (Hardness = 35 Shore A) to allow relatively unrestricted bender movement. A thin covering of much harder polyurethane resin (Hardness = 80 Shore A) holds the ceramics in place and provides a tough coating to protect the ceramics during insertion into the sediment. The received signals were amplified using a 40-dB gain amplifier located in the head of the receiver probes. A block diagram of the shear wave measurement system is presented in Figure 44.3. Shear waves are generated as a 6-cycle sine wave pulsed every 10 msec. Driving frequency (135–1120 Hz) and driving voltage (150–230 V p-p) varied depending on coupling characteristics, sediment shear wave velocity and attenuation, and the pathlength between receiver and transmitter. Transmitted and received signals were recorded with a digital waveform recording oscilloscope.

In October 1987 three isolated probes were used to test the system at the Diga site. The transmitter was placed by hand at 30 cm depth in the sediment and two receivers were inserted to 30 cm depth 200 cm on either side of the transmitter. The probes were inserted by hand to eliminate any electrical or mechanical connection between probes. After time-delay measurements were made, the receivers were moved successively in 25-cm intervals closer to the receiver. The resulting 17 distance vs. time delay measurements were plotted (Fig. 44.4) to determine the shear wave velocity (25.4 m/sec) and offset at nominal zero distance (0.013 cm). Receivers were then rotated 180° to demonstrate phase reversal of the received signal, a characteristic of shear and not compressional wave received signals.

The beam pattern of the combined transmitter–receiver system was investigated by rotating the receivers in a semicircle (50 cm radius) around the transmitter. The resultant 1.0 and 12.0 dB loss of signal at 45 and 90° suggests a wide beam pattern in the horizontal axis. A wide beam pattern in the vertical axis was demonstrated in a similar manner. These October trials proved that the shear wave probes could be used to measure accurately shear wave velocity up to distances of 200 cm, and that, because of the relatively wide beam pattern, the probes were insensitive to small changes in relative orientation.

In the March trials, the shear wave probes were rigidly attached to a 200 cm long stainless steel frame. The receivers were placed at 30 and 70 cm distance from the transmitter. A small amount of energy passed through the frame complicating the time-delay measurements. We were able to visually separate the frame-borne and sediment-borne signals by making time-delay measurements over a wide range of frequency (100–5000 Hz). In April the shear wave transmitter was potted in a 70 × 190 mm cylinder of silicone rubber that eliminated most of the energy transmission through the frame. For added isolation the receivers were potted for the July trials. The frame used for the April and July measurements was triangular (100 cm on a side) and held four compressional wave probes in addition to the shear wave probes (Fig. 44.5). Examples of received signals are presented in Figure 44.6.

Divers were required to deploy the current frame to avoid damage to the delicate probes. The next generation frame has been designed to operate independently of divers, and will contain probes to measure sediment temperature and electrical resistivity in addition to sediment shear and compressional wave velocity and attenuation. In this chapter we restrict ourselves to the presentation of *in situ* shear wave velocity.

Laboratory Measurements

Laboratory shear wave velocity measurements were made using the pulse technique described by Richardson et al. (1987). Shear waves were generated and received by bimorph ceramic bender elements cantilever mounted on a brass mass (Fig. 44.7). Transducers were electrically and mechanically isolated from each

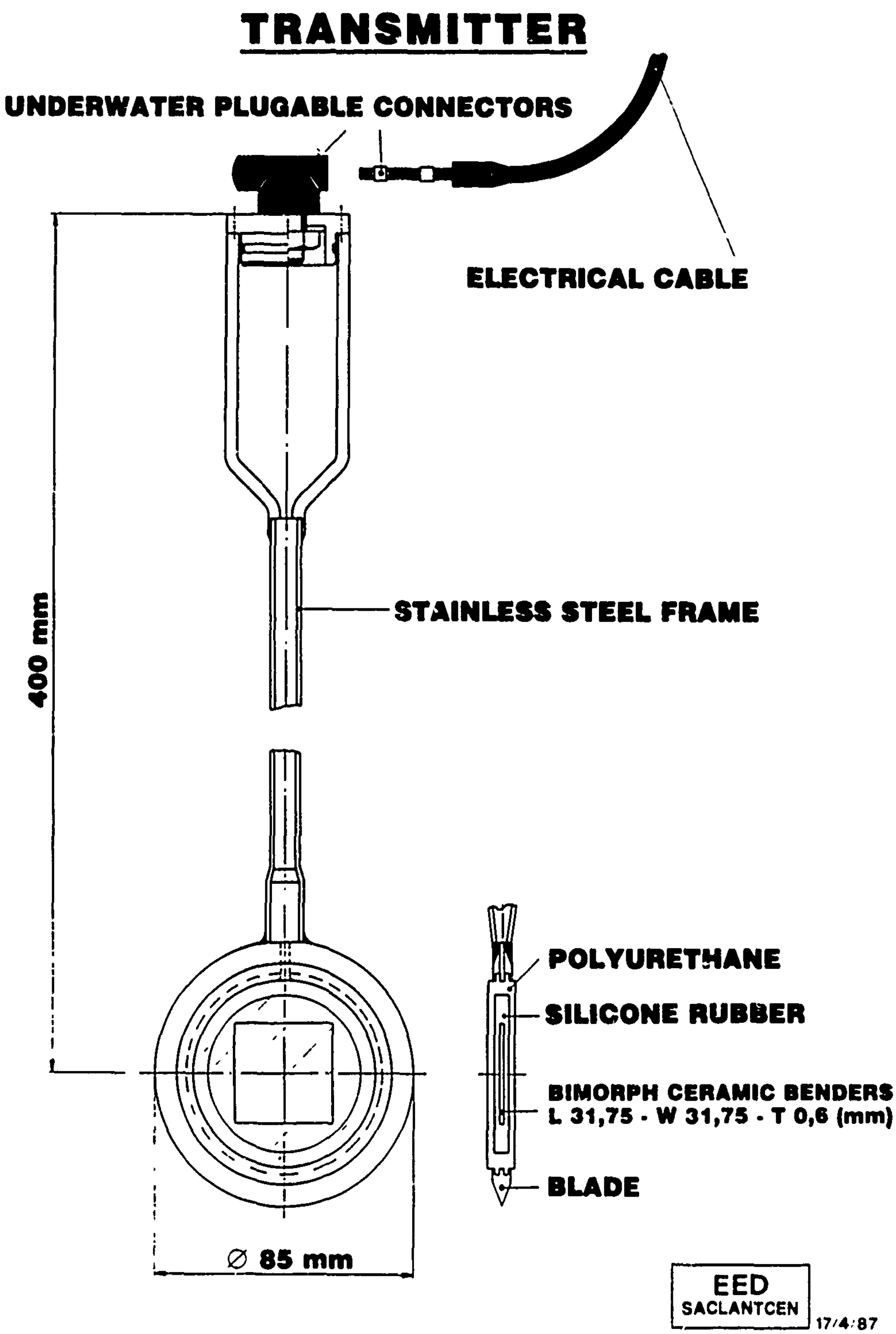

Figure 44.2. *In situ* shear wave transmitter (a) and receiver (b).

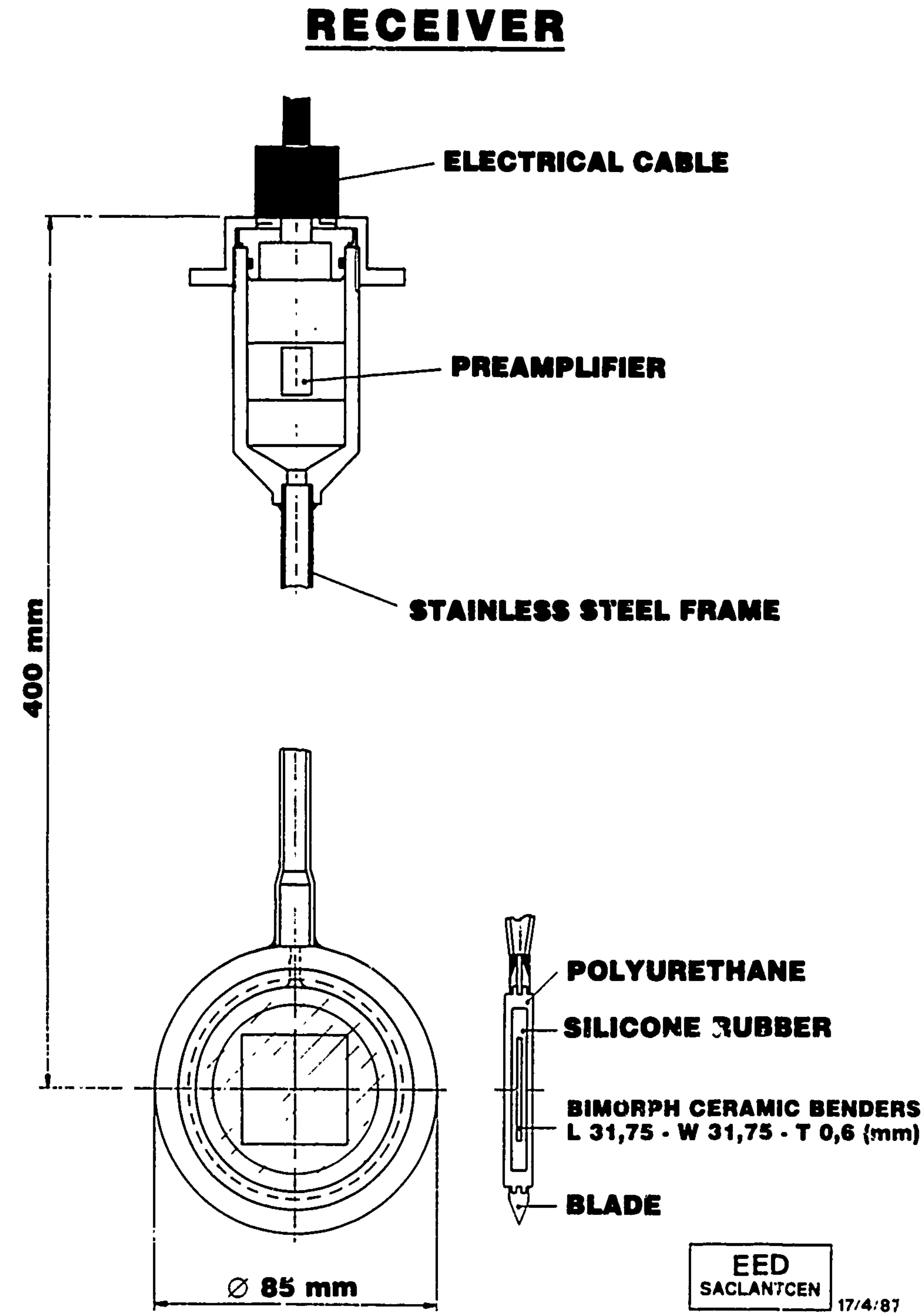
RECEIVER
ELECTRICAL CABLE
PREAMPLIFIER
STAINLESS STEEL FRAME
400 mm
POLYURETHANE
SILICONE RUBBER
BIMORPH CERAMIC BENDERS
L 31,75 - W 31,75 - T 0,6 (mm)
BLADE
∅ 85 mm
EED
SACLANTCEN
17/4/87

Figure 44.2. (b)

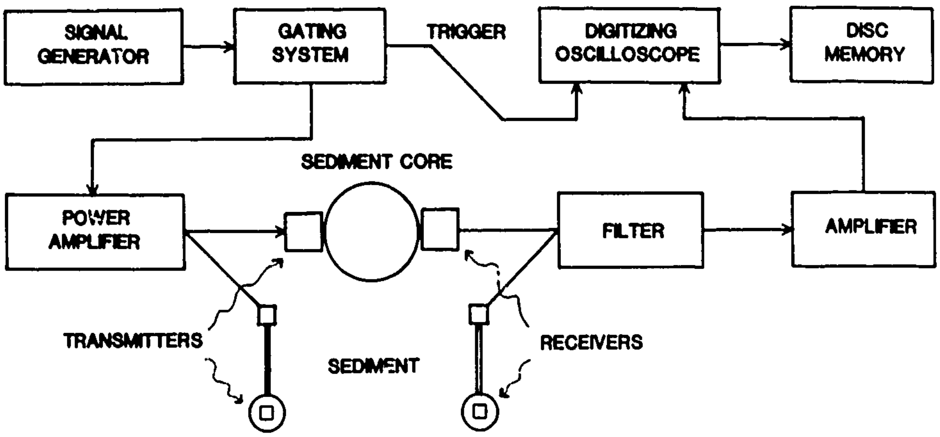

Figure 44.3. Block diagram of *in situ* and laboratory shear wave measurement system electronics. Preamplifiers (40 dB gain) located in the receivers are not shown.

other with rubber foam (Fig. 44.7) and the sediment was grounded to the electronics to eliminate electromagnetic feedover. The transmitter was driven by a 150–200 V p-p pulsed sine wave. Driving frequencies ranged from 150 to 1500 Hz depending on sediment type. The same electronic instruments were used to generate and record signals for *in situ* and laboratory shear wave measurements (Fig. 44.3). Examples of transmitted and received signals are presented in Figure 44.8.

Most time-delay measurements were made on sediments that remained in the 12 cm PVC cores. We drilled 3-cm-diameter holes in opposite sides of the core liner, snugged the transducers against the sediment suface, and recorded both time delay and distance between transmitter and receiver. Received signals were observed over a wide frequency range to separate shear wave signals transmitted through the sediment from those signals propagating along the core–sediment interface. Signals propagating along the core–sediment interface had lower amplitudes, much narrower bandwidths, and shorter time delays than shear wave signals transmitted through the sediment. Values of shear wave velocity measured on sediments removed from the cores were not significantly different from sediments remaining in cores. This suggested that we had successfully separated these signals. A time delay was subtracted from each measurement to account for the transit time of the signal through the electrical and mechanical system. This correction factor, measured with transducers touching, ranged from 2 to 14% of the sediment time-delay measurements (Fig. 44.8).

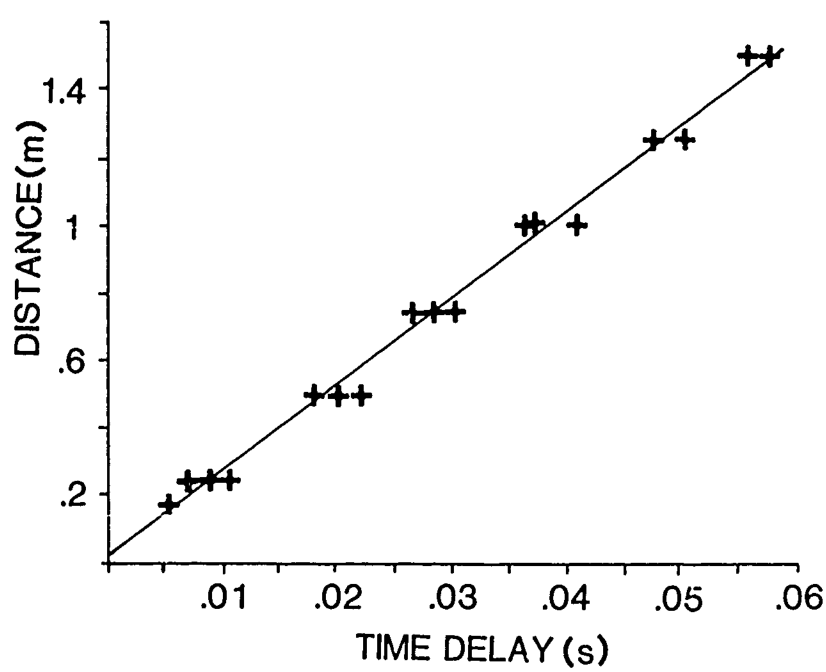

Figure 44.4. Shear wave velocity (25.4 m/sec) calculated from repetitive distance and time-delay measurements.

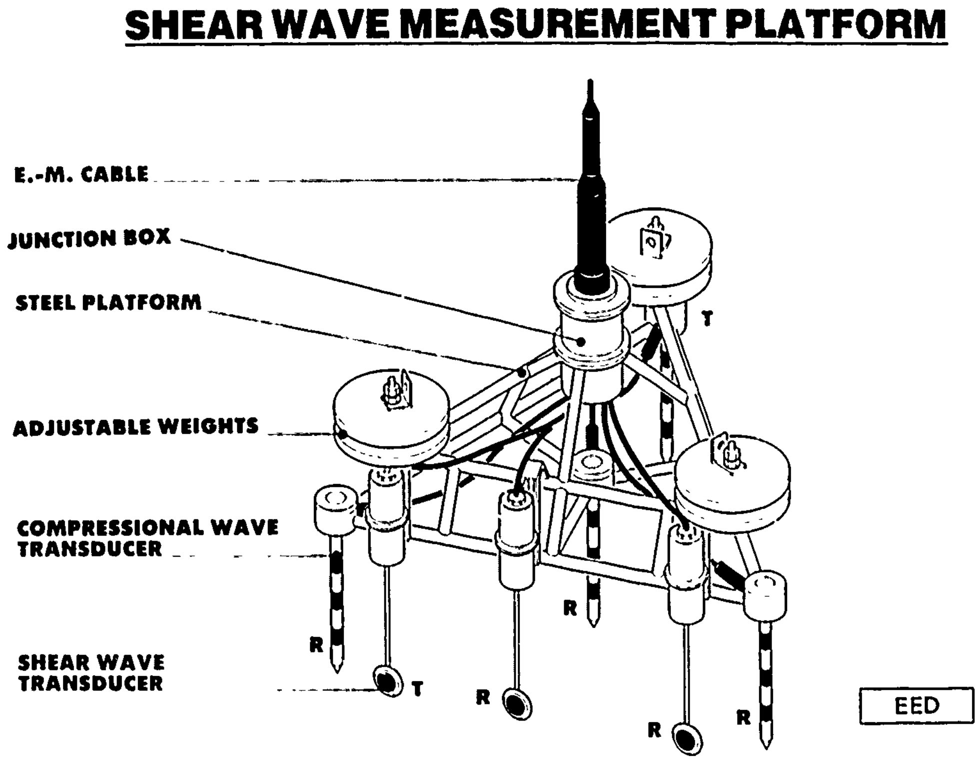

Figure 44.5. Acoustic shear wave measurement system as deployed in April and July 1988.

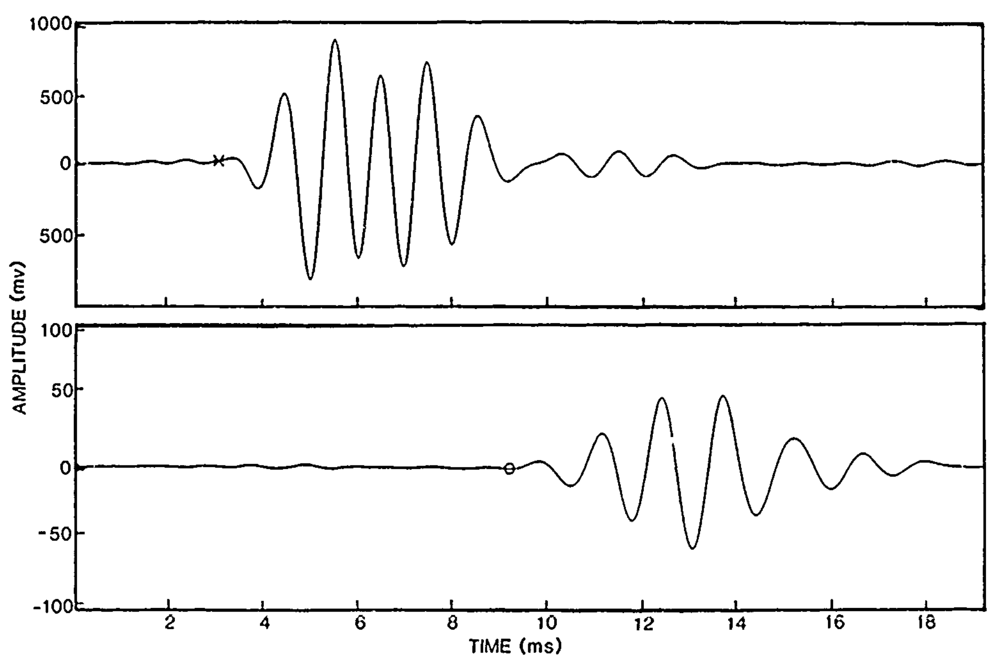

Figure 44.6. Examples of signals recorded from two shear wave receivers at the Venere Azzura site. Calculated shear wave velocities were 88.2 m/sec at 33 cm (top) and 82.4 m/sec at 71 cm (bottom) distance between probes.

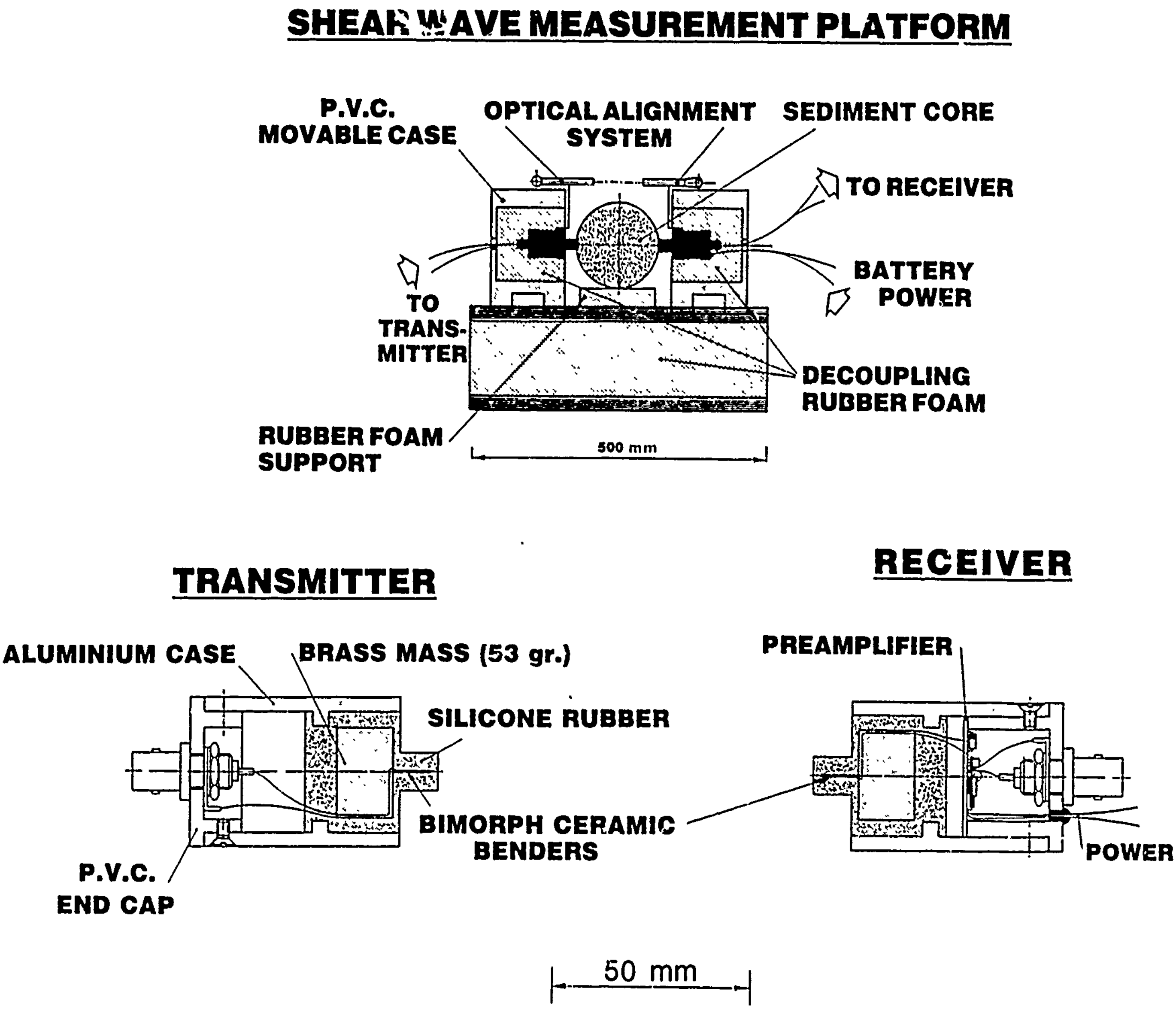

Figure 44.7. Laboratory shear wave measurement system.

Sediment subsamples were collected from the cores after laboratory shear wave measurements were completed. Dry-sediment density was determined with a helium pycnometer. Sediment porosity, void ratio, and wet density were calculated from weight loss of the sediment dried in an oven at 105°C for 48 hr, and from the measured dry density (Kermabon et al., 1969).

Results

Values of *in situ* sediment shear wave velocity ranged from 16.4 m/sec in the silty-clay sediments of Santa Teresa to 90.5 m/sec in the hard packed fine sands at Monasteroli (Table 44.2). Mean values of shear wave velocity measured on core sediments collected from the same locations were 6.5-22.1 m/sec less than mean *in situ* values. Shear wave velocity (*in situ* and laboratory) was negatively correlated with porosity and void ratio and positively correlated with sediment wet density (Table 44.3).

Discussion

The graphic relationship presented in Figure 44.9 suggests that laboratory values of shear wave velocity, measured at atmospheric pressure, can be corrected to *in situ* conditions using the following formula:

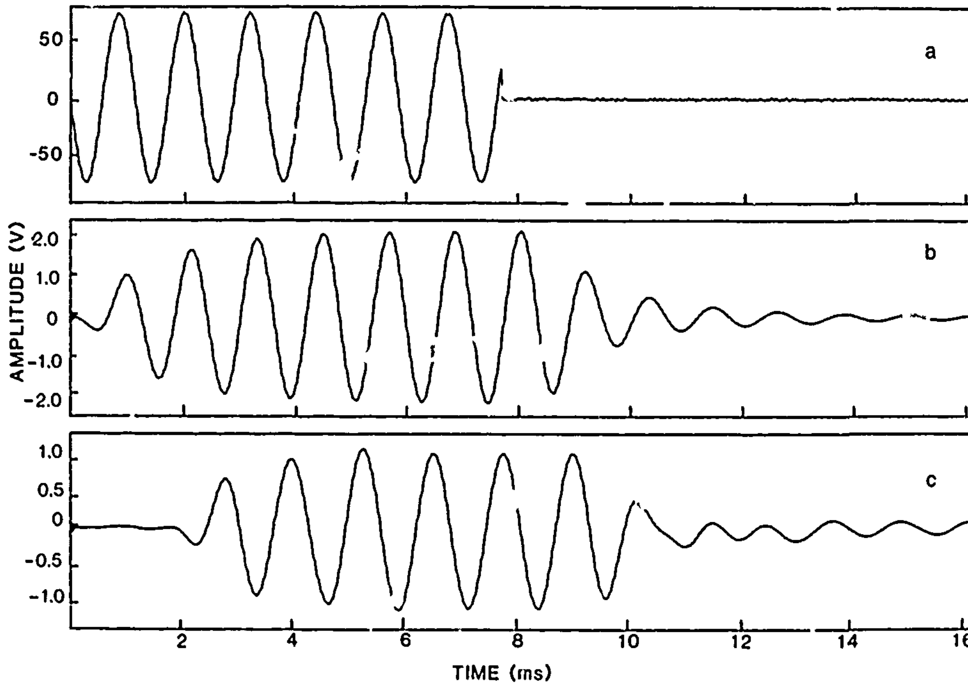

Figure 44.8. Examples of transmitted (a) and received signals for cored sediments collected at the Monasteroli site. The time delay with transducer and receiver touching (0.14 msec in b) was subtracted from time delay measured across 11.5 cm of sediment (1.86 msec in c) to calculate a shear wave velocity of 66.9 m/sec for this sandy sediment.

$$V_s\ (\textit{in situ}) = 10.43 + 1.17\ V_s\ (\text{Lab}) \tag{1}$$

In spite of the high correlation between these two measurements ($R^2 = 0.975$), this formula should be applied with caution to other data sets. The relation applies only to surficial sediments and should not be extrapolated outside of the limited range of the data set.

Richardson et al. (1987) listed several factors that might contribute to the differences in laboratory and *in situ* measured values of shear wave velocity. These included (1) disturbance of sediments during collection, handling and measurement, (2) changes in pore pressure and/or physical characteristics that result from the release of confining pressure when sediments are removed from the bottom, (3) differences in frequencies used for measurements, (4) differences in techniques used to measure shear wave velocities or shear modulus, (5) poor measurement techniques, and (6) natural variability of shear wave velocity in sediments. We can add (7) changes in sediment temperature, (8) differences in strain values used for measurements, (9) disturbance of sediments during insertion of probes, (10) creation of excess pore pressure during insertion of probes, and (11) the possibility of strong vertical gradients of shear wave velocity in near surface sediments.

We can dismiss eight of these factors for the current comparisons. *In situ* and laboratory shear wave velocity measurements were made with the same type of transducers at approximately the same frequencies and strain levels. Both laboratory and *in situ* transmitters were driven with a 150-230 V p-p pulsed sine wave. The resultant behavior of the sediments under these low strains (<0.00001%) is to be considered purely elastic, yielding

Table 44.2. Summary of values of shear wave velocity measured *in situ* and from core samples in the laboratory.

Site	Date	V_S (*in situ*) (m/sec)		V_S (lab) (m/sec)	
		Mean	Range	Mean	Range
Diga	6-7 October 87	25.4	22.0-27.0	15.6	13.7-18.1
Diga	14 March 88	27.0	25.8-28.2	16.2	11.9-19.8
Venere Azzura	15 March 88	78.8	65.7-89.9	61.4	60.5-62.9
Santa Teresa	17 March 88	19.7	16.4-23.3	13.2	10.2-15.4
Porotovenere	18 March 88	29.3	24.8-37.4	14.3	10.5-16.8
Turf	27 April 88	41.7	33.7-57.9	24.4	22.6-25.6
Diga	28 April 88	23.6	19.5-28.1	–	
Boa Dragaggio	30 April 88	40.2	37.0-45.3	22.4	19.2-29.1
Venere Azzura	25 July 88	77.4	69.7-88.6	–	
Monasteroli	26 July 88	83.4	75.7-90.5	61.3	55.6-70.8
Turf (sand)	28 July 88	74.0	72.1-75.7	53.7	46.6-61.1
Turf (mud)	28 July 88	41.6	34.6-46.8	21.1	16.8-25.1
Viareggio	29 July 88	27.1	24.1-33.0	14.9	12.9-17.9

Table 44.3. Pearson product-moment correlation coefficients (r) calculated between values of *in situ* and laboratory shear wave velocities (m/sec) and sediment physical properties.

	Porosity (%)	Void ratio (%)	Wet density (g cm^{-3})
V_S (lab)	−0.85	−0.82	0.85
V_S (*in situ*)	−0.91	−0.87	0.92

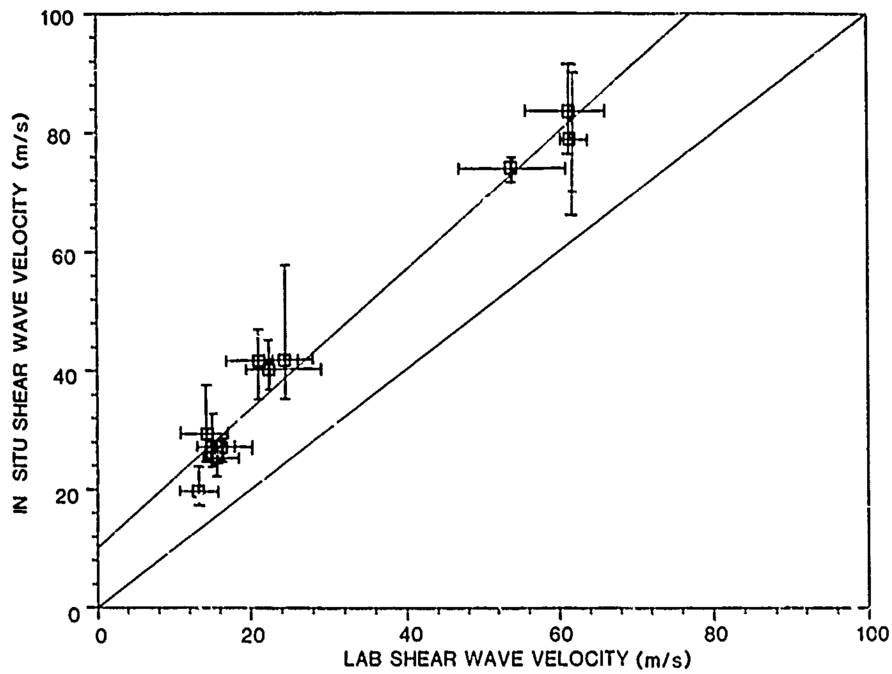

Figure 44.9. Comparison of laboratory and *in situ* shear wave velocities.

the maximum values of dynamic shear modulus and of shear wave velocity (Davis and Bennell, 1986). The resonant frequency of the pulsed sine wave, for both *in situ* and laboratory probes, ranged from 135 to 1500 Hz, depending on the mechanical impedance of the sediment. This frequency was generally lower for muds (135-430 Hz) and higher for sands (300-750 Hz). The time-delay measurements for single sediment specimens varied less than 5% over a wide frequency band (100-3000 Hz). The range of natural variability of values of shear wave velocity is presented in Figure 44.7 and preserves the basic relationships as reported. Values of shear wave velocity measured at sites sampled more than once were not significantly different in spite of differences in sediment temperature. The area disturbed by insertion of probes into sediments was small compared to pathlengths over which *in situ* shear wave measurements were made. At two sandy sites, *in situ* shear wave velocities made both immediately after probe insertion and after a 3-hr time delay. Shear wave velocities were the same, indicating excess pore pressures, created by insertion of the probes into the sediment, dissipated rapidly in these highly permeable, sandy sediments. Although great care was used to develop accurate measuring techniques, we cannot rule out systemic errors caused by poor techniques. The most likely causes for the lower laboratory shear wave velocities are sediment disturbances during collection, transportation, storage, and measurement both by mechanical manipulations and by changes in sediment confining pressures.

Numerous comparisons between values *in situ* and laboratory shear wave velocity have been made for terrestrial sediments using cross-hole and/or down-hole seismic techniques and laboratory resonant column tests (Cuny and Frey, 1973, Anderson and Woods, 1975; Anderson et al., 1978; Arango et al., 1978; Stokoe and Richart, 1975). Care must be taken in comparing these results to ours because strain amplitude, effective stress, time, and frequency of vibration must be accounted for (Davis and Bennell, 1986). Laboratory resonant column tests were run on sediments that had been subjected to effective confining pressures of up to 100 m, brought to the surface then compressed to *in situ* pressures. This can result in permanent changes in sediment microstructure. Our samples had no such stress history and no attempt was made to return sediments to *in situ* surficial conditions. In spite of these major differences in techniques, our results are in general agreement with comparisons of *in situ* and laboratory values of shear wave velocities reported for terrestrial sediments. Stoll et al. (1988), in a summary of these studies, reported values of *in situ* dynamic shear modulus to be 1.3-2.5 times the laboratory values. *In situ* dynamic shear moduli, calculated from values of shear wave velocity and density for this study, were 1.7-4.5 (mean 2.8) times calculated laboratory shear moduli (Table 44.4).

Akal et al. (1984, 1986) reported velocities of ducted Love waves from four of the sites occupied during this study. Measurements were made at short ranges (< 25 m) using stacked received signals from up to five ocean-bottom seismometers in series. Values of Love wave velocity (considered by Akal to be equivalent to values of shear wave velocity) at the Santa Teresa (16 m/sec), Portovenere (30 m/sec), Venere Azzura (65 m/sec), and Monasteroli (90 m/sec) sites were similar to *in situ* shear wave velocity values reported here. Akal's measurements at the

Table 44.4. Comparison of calculated and measured values of sediment dynamic modulus.*

Site	Date	Void ratio	Dynamic shear modulus (atm) Calculated	Lab	*In situ*
Diag	6-7 October 87	2.23	11.1	3.7	9.8
Diga	14 March 88	2.23	11.1	4.0	11.1
Venere Azzura	15 March 88	0.90	103.8	70.0	115.2
Santa Teresa	17 March 88	2.08	14.2	2.6	5.9
Portovenere	18 March 88	1.75	24.5	3.3	13.8
Turf	27 April 88	1.04	81.4	10.8	31.4
Boa Dragaggio	30 April 88	1.41	43.3	8.5	27.3
Monasteroli	26 July 88	0.78	128.0	70.9	131.1
Turf (sand)	28 July 88	0.75	75.4	54.1	102.7
Turf (mud)	28 July 88	1.13	73.5	7.8	30.3
Viareggio	29 July 88	1.63	29.9	3.5	11.6

Dynamic shear modulus was calculated from the empirical relationship between void ratio, confining pressure (effective stress), and shear modulus given by Bryan and Stoll (1988).

Monasteroli site were for sandy-gravel sediments, in contrast to the sandy sediments we collected. The depth of propagation of Love waves in the sediment was estimated to be between 0 and 3 m, complicating comparisons between techniques.

Bryan and Stoll (1988) summarized the effects of mean effective stress (p') and void ratio (e) on sediment dynamic modulus (μ) with the following relationship:

$$\mu = \mu_0 (p')^n \exp(\tau e) \tag{2}$$

where $\mu_0 = 2526$ atm, $n = 0.50$, and $\tau = -1.5$. The formula was based on 494 concurrent laboratory measurements of dynamic shear modulus, confining pressure (range 14–700 kPa), and void ratio (range 0.35–2.5) compiled from the literature. Overburden pressure (p_0) at 30 cm sediment depth was calculated from the void ratio and sediment wet density. Mean effective stress was set equal to $0.67p_0$, after Stoll et al. (1988), and the sediment dynamic modulus was calculated for each of our sample sites (Table 44.4). Sediment dynamic modulus (μ) was also calculated from mean values of sediment shear wave velocity (V_s) and wet density (ρ) using the following:

$$\mu = V_s^2 \rho \tag{3}$$

Values of calculated sediment dynamic shear modulus were nearly equal to or higher than *in situ* measured values and much higher than laboratory measured values. The calculated mean effective stress was low (less than 3 kPa) and probably quite variable at 30 cm depth in the sediment. This variability and the rapid increase in predicted dynamic shear modulus in the upper meter of sediment make more exact comparison difficult.

In the marine environment biological, chemical and physical processes alter surficial sediment (upper 1 m) properties (Richardson and Young, 1980, Richardson et al., 1983, Richardson, 1983). These processes can increase sediment dynamic rigidity by compacting the sediment or by increasing chemical bonding between particles. Sediment dynamic rigidity can be reduced by the feeding activities of bottom animals. Marine sediments can therefore either be underconsolidated or overconsolidated with respect to overburden pressures. Modification of

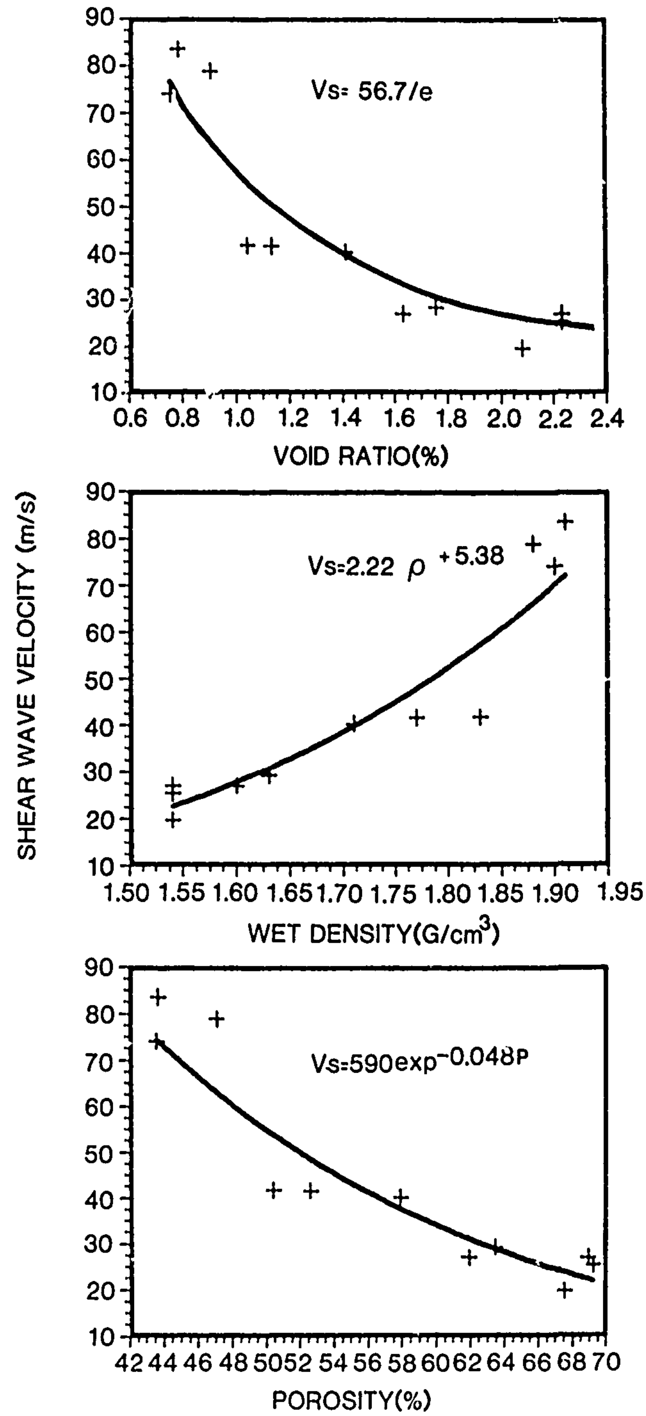

Figure 44.10. Empirical relationships between *in situ* shear wave velocity and sediment physical properties.

the formulations of Hamilton (1987) and Bryan and Stoll (1988) may be needed to predict sediment shear wave velocity gradients in the upper meter of sediment.

The empirical relationships between *in situ* sediment shear wave velocity and easily measured sediment physical properties (Fig. 44.10) provide reasonable estimates of surficial shear wave velocities for most marine sediments. Additional concurrent measurements are required to refine and extend this relationship to other sedimentary provinces. Hamilton (1971) suggests shear wave velocities should be highest in very fine sands with porosities of 45-55%. Sediments that are coarser or finer should have lower values of shear wave velocity because of a reduction in dynamic rigidity. The empirical relationship presented by Bryan and Stoll (1988) predicts an increase in sediment dynamic rigidity with increasing void ratio values over the range of 0.35-2.5%. Additional measurements of shear wave velocities are required to extend our empirical relationships to coarse sand and gravel sediments.

The rapid increase in shear wave velocity predicted for the upper few meters of sediment in reviews by Bryan and Stoll (1988) and Hamilton (1976, 1980, 1987) complicates comparison and predictions of sediment shear wave velocity. These empirical predictions were based on laboratory measurements of artificial, terrestrial and marine sediments and extrapolation of *in situ* seismic measurements to the upper few meters. Very few data are available on the gradients of *in situ* shear wave velocity in the upper few meters of marine sediments. An extensive measurement program is, therefore, required to define the varibility and vertical gradients of shear wave velocity in marine sediments.

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